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Mangrove environments of Port Darwin, Northern Territory: the physical framework and habitats

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Abstract

Port Darwin, with its mangrove-vegetated tidal flats, is a ria coast formed by the post-glacial marine flooding of a dissected plateau. The major ancestral riverine courses and the local terrestrial geomorphology have pre-determined the structure of the coast. The large-scale coastal units recognised in this study are: (1) narrow embayments; (2) broad embayments; (3) embayments with spits/cheniers; (4) islands; (5) riverine channels; and (6) open oceanic coast. Subsequently, depending on the interplay of sand/mud tidal sedimentation, terrestrial sedimentation, tidal creek erosion, wave erosion or equilibrium conditions, there have been developed a wide range of medium-scale geomorphic units: (1) tidal flat/hinterland contact, (2) high tidal alluvial fans, (3) the main tidal flat, (4) tidal creeks, (5) spits/cheniers, and (6) rocky shores. Each of these units have their own suite of substrate types.

Stratigraphic analyses show that much of the tidal lands are infilled terrestrial lowlands. The main tidal flat accumulation has resulted in a wedge of mud which interdigitates with gravel/sand deposits developed along the hinterland edge, and with sand deposits of the spits/cheniers. On the sandy coasts the stratigraphic interval is composed of sand overlying bedrock. Sediment discharge from the hinterland and fluviatile sources continue to accrete sediment along the tidal flat edges. The stratigraphy also shows that muddy tidal flat coasts, spit/chenier coasts and rocky shores are long-term stable features.

The stratigraphic/lithologic system forms the framework for both the tidal flat hydrologic system and the tidal flat/hinterland hydrologic exchanges. Soilwater and groundwater regimes are linked closely to stratigraphy, subtrate, recharge mechanisms and evapo-transpiration. The salinity of groundwater and soilwater on tidal flats shows a graded increase in value from seaward mangrove environments through to salt flats, with a decrease in values along the freshwater-influenced hinterland margin and alluvial fans.

The interplay of substrate type, salinity and tidal level results in a proliferation of habitat types which have distinct mangrove assemblages. These habitat types correspond to geomorphic unit types. Eight broad mangrove assemblages have been recognised in the Port Darwin region; these are: (1) hinterland fringe assemblage inhabiting the tidal flat/hinterland contact: (2) alluvial fan mangrove assemblage, inhabiting high tidal alluvial fans; (3) main tidal flat mangrove assemblage; (4) creek bank assemblage; (5) creek shoal assemblage; (6) creek mouth assemblage; (7) spit/chenier assemblage, inhabiting margins of spits/cheniers; and (8) rocky shore assemblage. Within the habitats there are local small scale gradients in salinity, soil types and frequency-of-inundation which result in zonation within any given assemblage.

Introduction

This paper reports on studies conducted over several years on the tidal flats and mangroves of Port Darwin (Fig. 1). The first most comprehensive published work on the Darwin area dealt with the hinterland and described landforms, soils, geology, vegetation and land use of the Katherine-Darwin region with brief description of the littoral vegetation (Christian and Stewart 1953). Subsequently publications have dealt with regional geology (Bureau of Mineral Resources 1961), regional bathymetry (Hydrographic Service, RAN 1973) and climate (Bureau of Meteorology 1976), but there are no published detailed studies on the coastal sector. The flora and fauna, both marine and terrestrial, have been described in Christian and Stewart (1953), Blackburn (1975), Gow (1977) and Fogarty *et al.* (1979).

Mangrove species and the various fauna in mangals of Darwin have been listed by Saenger *et al.* (1977) and Wells (1982) as part of their regional studies of Northern Australian mangroves. Some data on mangrove environments of Port Darwin also are scattered in numerous unpublished reports which are retained by various government, industrial or private organisations. Such studies, however, were initiated *ad hoc* to gather data relevant for a particular project and the results have limitations in that they do not provide an overview (framework) of the environment for the Port Darwin mangroves because they are oriented toward specific problems.

The objectives of this paper are to provide:

- firstly, a description of the Port Darwin area in terms of its morphology, stratigraphy, substrates and hydrology, all of which are useful in understanding the basis of the mangrove systems;
- secondly, a classification of mangrove habitats and assemblages of Port Darwin; and
- finally, a brief description of the mangrove assemblages in terms of distribution and composition.

A second paper describing in more detail the structure, composition and zonation of the mangrove assemblages and their relationship to habitats of Port Darwin is in preparation.

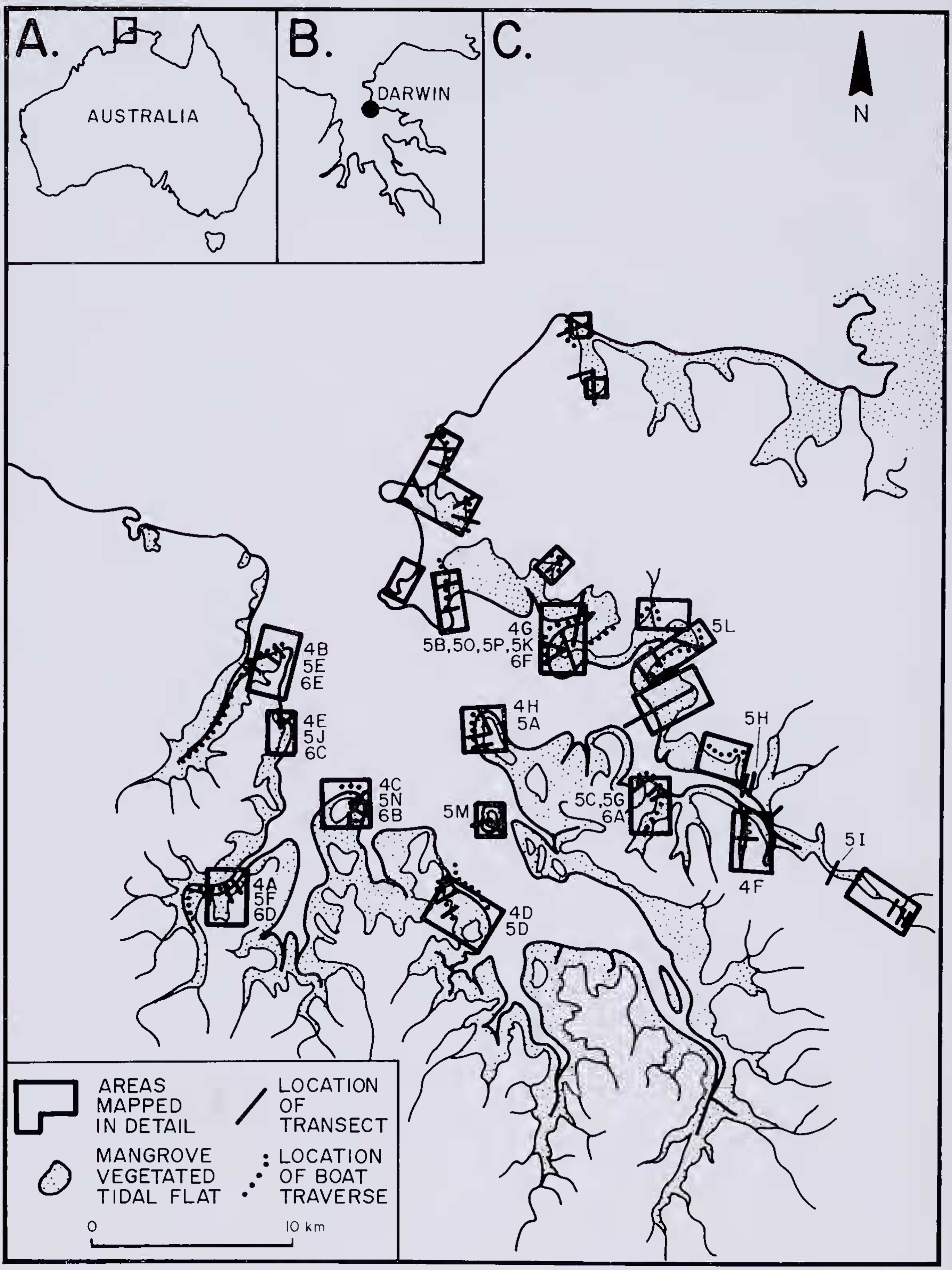

Figure 1.—Maps showing study area and location of study sites (mapped area) transects, boat traverses. Numbers alongside designated mapped areas refer to Figure numbers wherein maps and profiles are illustrated in more detail.

Methods

Mangrove-vegetated tidal flats are a complex product of natural physico-chemical and biological interactions. Accordingly, in documenting these systems, it is necessary to use an interdisciplinary approach, utilising data on regional setting and processes with that of the local environment, and integrating data on physiography, oceanography, hydrology, chemistry, sedimentology, stratigraphy, and biology.

A three-phased approach was used in the documentation of mangrove environments of Port Darwin. Firstly, with coloured aerial photographs the main large-scale coastal types were identified (Table 1): (1) narrow embayments, (2) broad embayments, (3) spit/chenier-lined embayments (4) islands with spits and connecting tidal-lands, (5) riverine embayments, (6) oceanic rocky shores, and (7) oceanic sandy shores. Secondly, the various phototones within a mangrove-lined coastal type were checked by transects through mangrove zones, by lengthy boat traverses along the seaward mangrove fringe and creek banks, aided by spot checks (by vehicle, boat or helicopter). The main phototones investigated were: (1) mangroves on high-tidal alluvial fans, (2) mangroves fringing the hinterland, (3) high-tidal mangroves fringing spit/cheniers, (4) stands of *Ceriops,* (5) stands of *Rhizophora,* (6) stands of *Sonneratia,* (7) stands of *Avicennia* (mixed with other species). (8) stands of *Rhizophora/Camptostemon,* (9) salt flats, (10) cyclone-destroyed (vegetation-clear) patches within *Rhizophora* stands, (11) cyclone-cleared patches within *Ceriops* stands, (12) terrestrial parts of spits/cheniers, (13) rocky shores. (14) mid-low tidal flats, (15) small-scale (*ca* 1 m) cliffs, (16) terrestrial freshwater drainage/vegetation units and (17) the terrestrial hinterland and its vegetation.

Table 1

Distribution and relative abundance of medium-scale geomorphic tidal units within large-scale morphologic units

MAJOR UNIT	MEDIUM-SCALE GEOMORPHIC UNIT
Narrow embayments	tidal flats > hinterland margins > tidal creeks > alluvial fans ⩾ rocky shores
Broad embayments and spit/chenier-lined embayments	tidal flats > hinterland margins > tidal creeks spits/cheniers > alluvial fans ⩾ rocky shores
Islands	tidal flats > spits/cheniers ⩾ rocky shores
† Riverine embayments	steep banks, cliffs, shoals, narrow tidal flats, hinterland margins, alluvial fans
* Exposed cliff rocky shores	rocky pavements, rocky slopes, cliffs
* Exposed sandy shores	sand beaches, beach ridges and coastal dunes

† not considered further in this paper because this unit is assigned to the Riverine Zone of the regional system.

* not considered further in this paper because these units generally do not support mangals; they are included only for completeness.

Thirdly, selected areas were investigated in more detail along (some 36) transects to study geomorphology, substrate, stratigraphy, soil/groundwater salinity, fauna and flora (Fig. 1C). Sampling of flora/fauna generally was not extended to below MSL because the study concentrated mainly on mangrove environments. Mangrove vegetation composition, height, canopy structure and distribution was documented by continuous belt transect to verify disposition of zones and their phototones. At selected intervals, usually in the middle of a zone or phototone, the composition and density of the vegetation was quantified within five replicate 5 m x 5 m quadrats. In many locations ten, fifteen or twenty replicates were used because of low numbers of individuals or variability of composition. In total some 3 000 quadrats were counted.

Substrate and groundwater/soilwater were sampled at the same sites as vegetation. Soil, excavated to 30 cm, was described in terms of: colour, structure, fabric, texture and composition. The surface soil, the soil at 25-30 cm depth and the groundwater table were sampled for salinity analyses. Soil samples were hermetically sealed and frozen, and thawed only when ready for laboratory analysis. Groundwater samples, and water extracted from soil samples, were analysed for total dissolved solids by evaporation technique.

The stratigraphy of sites was investigated by pits (0.3-1.2 m deep), auger (0.3-4 m deep), and by probing with an extendable rod to 8 m deep. With probing the following rock/sediment types could be differentiated in the subsurface: (1) mud, (2) sand, (3) rock, (4) gravelly sediment, (5) muddy sand, (6) interlayered sandy and muddy sediment.

At all sampling sites along the transects note was made of processes that were important to the tidal flat system. In many instances the processes could be directly observed, otherwise it was necessary to document the products and hence infer the processes. Some of the main processes and products noted were as follows: *(1) physical:* wave reworking of substrates producing cleanly washed sand/gravel; fluviatile sheetwash from the hinterland during the wet season, producing aprons of sand along the hinterland edge; tidal current/wave action erosion of mud, producing small steep cliffs; seepage of freshwater, diluting the normal tidal flat water; seepage of marine water from slope of sand bar beaches; *(2) chemical:* alternating oxidation/reduction of substrates at groundwater table, producing Fe colour mottles in substrates; precipitation of $CaCO_3$ and ironstone, producing illuvial hardpans; precipitation of halite from soilwater, producing a surface efflorescent on the salt flat; *(3) biological:* burrowing by fauna, producing bioturbation structures, open burrows and burrow excavations; predation by fish, producing fragmented shells; binding of substrates by vegetation pneumatophores and other roots.

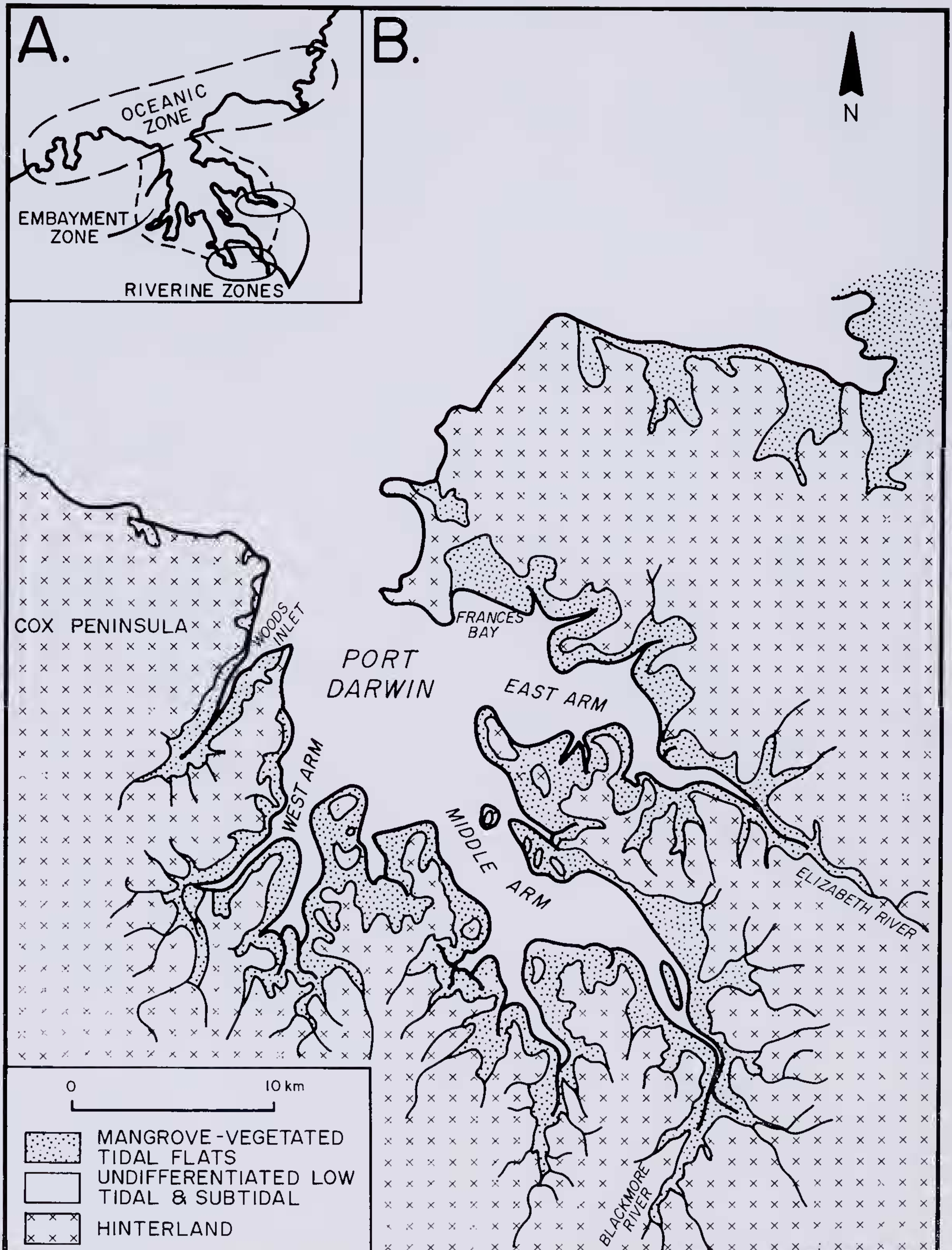

Figure 2.—A. Map showing regional characterisation of Port Darwin area into Oceanic, Riverine and Port Darwin Embayment zones. B. Map of Port Darwin showing distribution of mangrove-vegetated tidal flats.

Results

Description of Port Darwin Environment: Regional Setting

Climate

Darwin has a tropical humid climate (Aw of Köppen 1936) with two major seasons: a summer wet season which may be classed as monsoon, and a winter dry warm/hot season. Bureau of Meteorology (1976) data show that Darwin has some 97 rainy days per year with about 1,500 mm of precipitation. Mean maximum summer temperature in January in 32.2°C; mean minimum summer temperature is 25.0°C. Mean maximum and mean minimum temperatures in winter in July are 30.4°C and 19.6°C, respectively. Evaporation is 2,773 mm per year with a monthly minimum of 187 mm during February, and a monthly maximum of 285 mm during October.

Wind originates from various sectors dependent on the time of day and season (Bureau of Meteorology 1973). In winter it originates from southeast (and in addition south and east) sectors in the morning and may shift to east, southeast (and north) sectors in the afternoon with average speeds of 2.5-2.8 m/sec.; in summer, it originates from a variety of sectors but mainly from west, northwest and south in the morning and shifts to west, northwest and north sectors in the afternoon with average speeds of 2.6-3 m/sec. Storms in the summer generally approach from the west, north and northwest. Periodically tropical cyclones impinge on the coast. These are associated with destructive winds, substantial rainfall and storm surges.

Oceanography/Riverine Hydrology

Port Darwin tides are macrotidal; the maximum range is 7.8 m; the mean spring range is 5.5 m and the mean neap range is 1.9 m (Australian Tide Tables, 1983). Tidal currents measured near the main jetty are 0.25-1.4 m/sec. Landbreeze/seabreeze systems and thunderstorms generate local waves which are an important prevailing feature in the coastal zones in that they develop spits, sand bars and cheniers on the exposed portions of the coastline.

Port Darwin functions seasonally as a large estuary because, during the monsoon and shortly afterwards, the main rivers discharge substantial quantities of freshwater into the marine system. There is also a substantial input of freshwater from the surrounding hinterland by sheet flooding and by the numerous small creeks and streams. Subterranean freshwater seepage from the hinterland also continues as an important phenomenon well into the dry season.

Regional Coastal Morphology (Large Scale Units)

The Port Darwin area is a large indented embayment some 450 km² in area (Fig. 1). The hinterland is a dissected plateau underlain by Precambrian rocks with a variable cover of Cainozoic laterites and weathering products (Christian & Stewart 1953). The hinterland landforms have determined to a large extent the disposition of coastal and marine landforms and environments within Port Darwin.

Two major rivers, the Elizabeth and the Darwin River/Berry River drain into Port Darwin. The disposition of these rivers and their distributaries has controlled the *regional scale structure* and *shape of Port Darwin*. The (post-glacial) marine flooding of the Elizabeth River has developed East Arm; flooding of the Darwin and Berry Rivers has developed Haycock Reach, and flooding of various tributaries has developed West Arm and Woods Inlet.

The regional large-scale morphology in this study area can be categorised as (Fig. 2):

(1) *Riverine channels,* which constitute the headwaters of the main rivers/creeks that drain into Port Darwin; Holocene riverine processes are dominant in shaping both the medium scale geomorphology and sedimentation patterns; there are steep tidal river banks, riverine shoals and channels, and freshwater flow that seeps into and interacts with the marine environment.

(2) *Open oceanic coastline,* comprised of rocky and sandy shores that front the open Timor Sea; locally there are small embayments.

(3) *The Port Darwin Embayment,* formed by the marine flooding of the dissected Pleistocene terrain.

Embayment-dominant environments of Port Darwin form the main emphasis of study for this paper. Riverine and oceanic environments are not discussed further.

Physical Features of the Port Darwin Embayment

Geomorphology

Prior to the post-glacial transgression, Port Darwin was a dissected terrain which had a subdued drainage, scattered subplanar lowland plains and wetlands, scattered hillocks, knolls and hills, and riverine courses. Marine flooding and sedimentary infill of this terrain has resulted in a development of narrow embayments, broad embayments, islands and tidal land connections between these islands. At the large scale the shoreline of this embayment-dominated system can be subdivided into the following *intergradational* units (Fig. 3):

(1) *Narrow embayments,* where relatively narrow riverine courses have been flooded by the post-glacial transgression and infilled with tidal deposits (mud).

(2) *Broad embayments,* where open undulating terrain has been flooded by post-glacial transgression and filled with tidal deposits.

(3) *Embayments with spits/cheniers,* as for (2) above but with more exposure to waves such that reworking of sediments develops spits/cheniers.

(4) *Islands,* where hills of the original terrain have been isolated by marine flooding and tidal deposits; these islands, where exposed to wave action, have *bordering spits/cheniers,* and where protected, have muddy *tidal-land connections* with the mainland or other islands. The islands are gradational from large-scale features such as Quarantine and Channel Islands to small hillocks on the tidal flat.

The medium-scale coastal geomorphology of the Port Darwin embayment, has been determined by the finer-scale geomorphology of the hinterland and by processes of marine sedimentation and erosion. Thus, protected embayments have accumulated a mud wedge (tidal flat) which is locally dissected by tidal creeks. Semi-protected embayments have accumulated mud wedges (tidal flats) with encroaching sand spits and cheniers formed by wave reworking and tidal dispersion. Exposed localities either have rocky shores swept clear of major sedimentary accumulations or have spits which develop muddy accumulations on their protected side.

Subsequently, depending on the result and interplay of mud sedimentation, sand sedimentation, tidal creek erosion, wave erosion, or equilibrium conditions, there have been a wide range of medium scale tidal and subtidal zone geomorphic units that generally are either peripheral to the main Port Darwin embayment shoreline, or circumferential to islands. The units are (Fig. 3):

(1) Hinterland margin
(2) Alluvial fans
(3) Tidal flats
(4) Tidal creeks
(5) Spits/cheniers
(6) Rocky shores
(7) Subtidal channels and bays

The disposition of these medium-scale geomorphic units are shown for selected small areas in Fig. 4. All these units except subtidal channels and bays support mangroves to some extent.

(1) *Hinterland margin:* these units (10-50 m wide) form the junction of the hinterland and tidal flat; they are inundated only on the highest tide and are underlain by reworked colluvium or muddy sand washed off the hinterland; the unit is subject to freshwater seepage.

(2) *Alluvial fan:* these alluvial accumulations, fan to deltoid in shape, form in high tidal environments where creeks and streams debouch onto tidal flats; substrates are sandy/gravelly and mixed with mud; the fans are subject to freshwater seepage.

(3) *Tidal flats:* These are broad (100 m to more than 1 km) gently inclined surfaces underlain by sand in low tidal levels and mud or muddy sand/sand in mid-high tidal levels; generally mud is the more common substrate in mid-

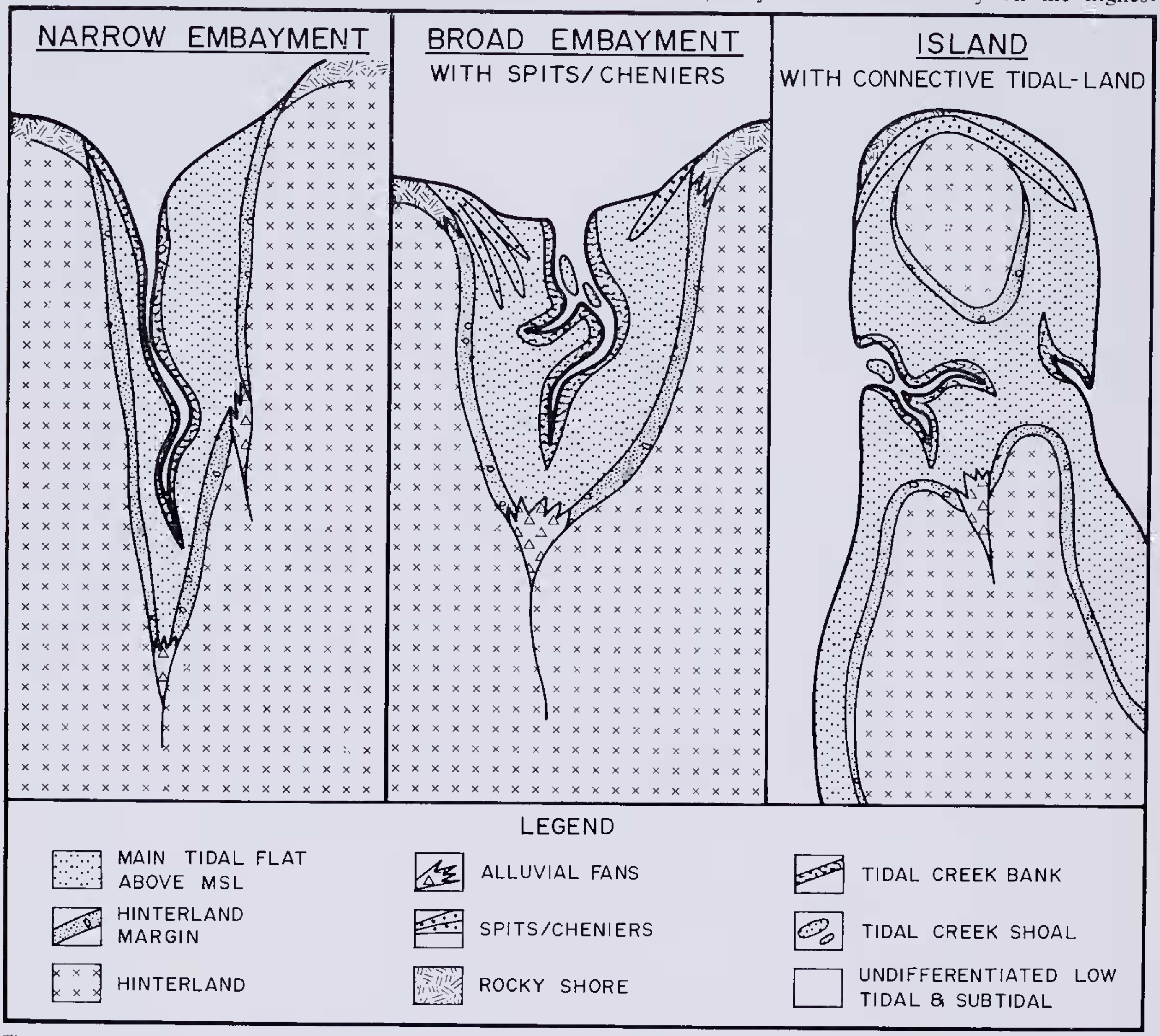

Figure 3.—Schematic diagram showing three types of coasts in Port Darwin. Within each coastal type there is a similar range of medium-scale tidal-zone geomorphic units.

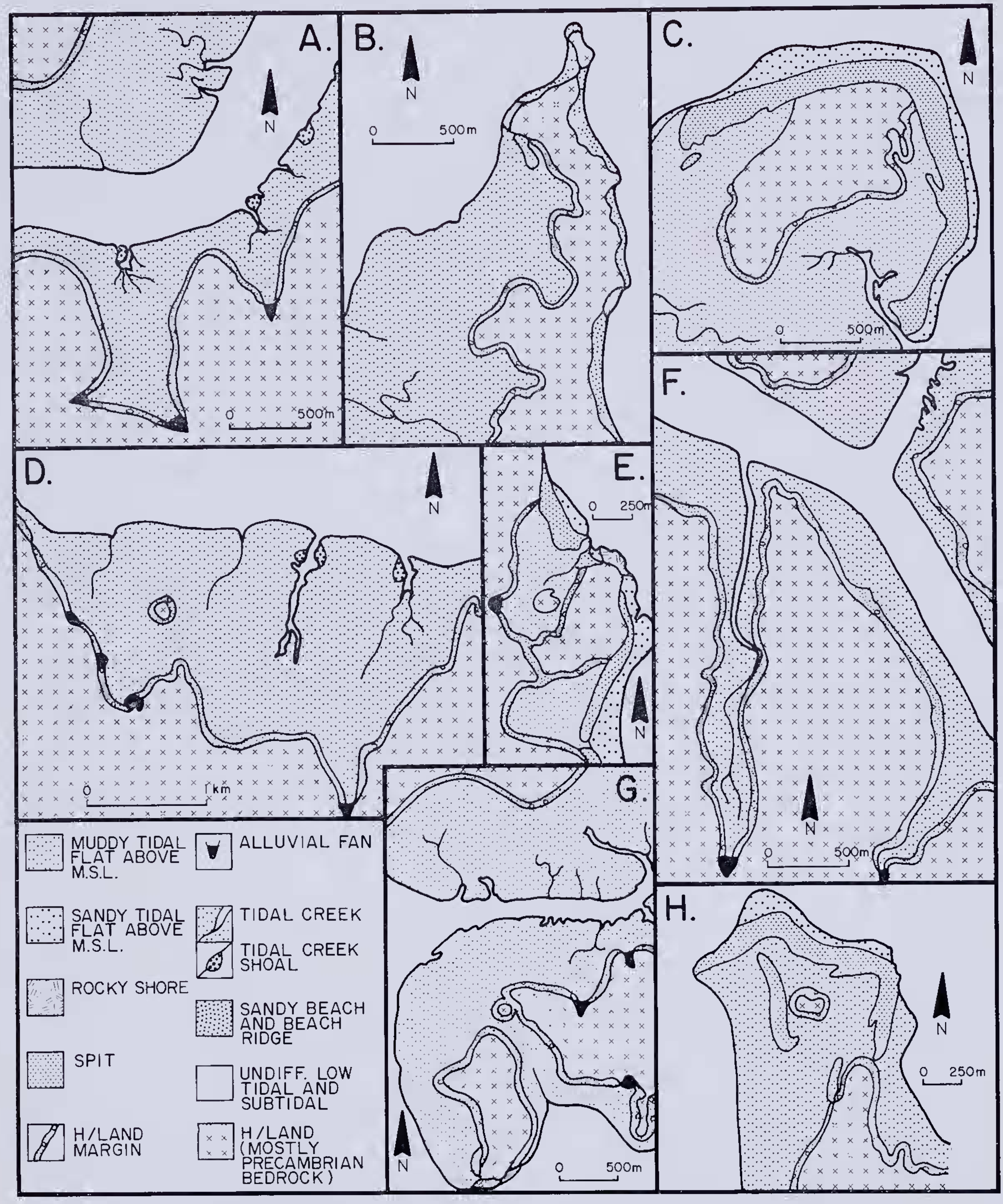

Figure 4.—Maps of selected small areas in Port Darwin to illustrate the distribution and interrelationship of medium-scale geomorphic units. The location of the areas is shown in Fig. 1. These maps also show: the various stages of island development and isolation (compare A, E, G and C); the intergradation of embayment shapes (compare B, D, A and E); the range of geomorphic units within any area; the various sizes of islands that are isolated by tidal-lands (compare C, D, E, G and H).

high tidal levels but sand is common where tidal flats front a spit/chenier system; mid-high tidal flats are vegetated by mangroves. A *salt flat* is developed at high tidal levels where mangroves have died back due to the development of a highly hypersaline groundwater/soilwater field. Locally the mangrove-vegetated tidal flat is truncated at its seaward margin by a small (1-2 m) cliff cut into tidal-flat muds.

(4) *Tidal creeks:* these are erosional channels (3 m-100 m wide, and approximately 2 m-10 m deep) that meander and bifurcate across tidal flats; creeks may be clogged with shoals.

(5) *Spits/cheniers:* these are elongate, narrow (10-50 m wide) sand/gravel deposits which are wave-developed features; spits typically emanate from exposed to semi-exposed headlands; cheniers are detached from headlands.

(6) *Rocky shores:* these are steeply inclined to cliffed, fissured to bouldery shores comprised of rock or rock boulders; these shores generally are wave-exposed environments.

(7) *Subtidal channels and bays:* these are the permanently-inundated environments that adjoin the tidal zone units listed above; the units are underlain by rock, sand or mud depending upon which tidal zone unit is adjoining. These units are not discussed further in this paper.

The distribution and relative abundance of these medium-scale units in relationship to the large-scale geomorphology is summarised in Table 1. Origin of the units is summarised in Table 2. Typical distribution of the units is shown in Figures 3 and 4.

Substrates (Soils)

There are a wide variety of substrates in this study area, however, all can be related to geomorphology and associated processes. In the Port Darwin area there are four major settings for substrates and each have generated distinctive suites of substrates. The settings are ordered below in decreasing wave exposure.

(1) exposed rocky shores
(2) exposed sandy shores
(3) semi-protected embayments with spit/cheniers
(4) sheltered muddy shores
(5) terrestrial/tidal flat junction

The processes significant for the generation of the suites of sedimentary (substrate) products are: 1) sediment supply, which determines whether the shores are rocky or covered with sediment; 2) wave and tidal energy, which determine whether the shores are winnowed free of sediment or are covered by winnowed sand; 3) wave exposure, storm action, and frequency of flooding, which determine that the shores are underlain by sand in low tidal zones and by mud in progressively high tidal zones, and 4) fluviatile input, which determines the amount of coarse sediment (sand and gravel) that is discharged along the hinterland edge and high tidal alluvial fans.

Table 2

Origin of geomorphic units

GEOMORPHIC UNIT	ORIGIN	
	MAIN PROCESSES	DETAILS OF PROCESSES
Hinterland	ancestral topography	current processes of terrestrial pedogenesis, erosion, transport and sedimentation
Hinterland/tidal flat margin	marine reworking and terrestrial sedimentation	marine reworking of colluvial deposits; zone of mixing between muddy tidal flat sediments and hinterland; later, on-going sedimentation (sheet-wash off terrestrial environments) contributes to this unit
High tidal alluvial fan	terrestrial sedimentation and marine reworking	fluvial discharges of sediment from creeks onto high-tidal flats; sedimentation keeping pace with tidal flat accretion develops an interdigitating stratigraphic relationship between alluvial gravel/sand and tidal flat muddy sediments. Further sedimentation builds the alluvial fan up above the level of the tidal flat (salt flat)
Main tidal flat	tidal flat sedimentation	sedimentary progradation develops a tidal flat wedge, the upper surface of which is the low-inclined tidal surface which is colonised by mangroves between MSL and MHWS; evolution of a high-tidal hypersaline groundwater/soilwater causes mangroves to die back and there is patchy development of a salt flat
Tidal creek	marine erosion	marine erosion of the tidal flat by drainage incisions
	marine sedimentation	accumulation of sediments develops local shoals
Spits/cheniers	marine sedimentation	wave processes acting on rocky headlands at high tidal level cause the migration and progradation of linear shell grit and sand deposits
Bouldery and rocky intertidal shore	marine erosion and marine reworking	formed by marine erosion of spurs of a rocky terrain and marine reworking of their colluvial or soil-covered slopes

Table 3

Substrate/soil types *

GEOMORPHIC UNITS	TYPES OF SOILS	SOIL DESCRIPTION				
		STRUCTURE	FABRIC AND TEXTURE	COLOUR	WATERLOGGING	SOIL SALINITY
Hinterland/ tidal flat contact	rock gravel sheets boulder deposits interlayered mud/sand,	structureless varying to mottled	gravel or sand framework with interstitial mud	grey to brown	waterlogged during wet season and after (infrequent) tidal flooding	depending on freshwater seepage there may be a gradient of $\sim 14^{0}/_{00}$ up to $48^{0}/_{00}$
High tidal alluvial fan	rock gravel sheets bioturbated and root-structured mud, mud/ sand and sand	layered, varying to burrow-mottled and root-structured	a grain framework of fine, medium and coarse sand varying to gravel, locally with interstitial mud	mainly brown, grey at depth	waterlogged during wet season, otherwise saturated in phreatic zone (usually 50 cm deep)	gradient $< 1^{0}/_{00}$ to $39^{0}/_{00}$
Tidal flat	bioturbated and root-structured mud, homogenous mud, texture-mottled mud and sand, muddy sand, and sand	homogenous, mottled to root-structured	mainly mud with less amounts of sand	grey to brown	waterlogged most of the time	gradient MSL $\sim 33^{0}/_{00}$ up to $196^{0}/_{00}$ at salt flat
Spits/ cheniers	homogeneous sand, laminated sand, inter-layered sand/mud	layered	a grain framework of medium to coarse sand and shell gravel	cream to buff	waterlogged during high tide; well-drained during ebb tide	gradient of $42^{0}/_{00}$-$73^{0}/_{00}$
Bouldery or rocky head-land shore	rocky gravel sheets, boulder deposits	structureless to imbricated	boulder or pebble framework with patchy interstitial mud; rock crevices with infiltrated (geopetal) sand/mud	interstitial mud is grey	waterlogged during high tide; well-drained during ebb tide	gradient of $\sim 30^{0}/_{00}$ at MSL to $> 46^{0}/_{00}$ above HWN

* soils developed on the supratidal/terrestrial hinterland are not described since they do not support mangroves.

The main materials composing substrates are mud, sand, shell, rock gravel and bedrock. Mud is clay minerals and quartz silt, and is mainly fluviatile; sand is quartz, rock fragments, or comminuted shell; shell is the accumulated tests of the marine benthos; rock gravel is eroded hinterland rocks, or is marine-reworked colluvium; bedrock is the metamorphic rock of the hinterland. The components of mud, sand, shell and rock gravel when accumulated and/or mixed develop a wide variety of substrate types. The effect of burrowing biota such as crabs serves to further mix the sediments and produce homogeneous and bioturbated or burrow-structured substrates. Vegetation contributes to substrate variability by input of detritus and by bioturbation (root structuring).

The main substrates encountered in this study in order of abundance include:

(1) bioturbated and root-structured *mud*
(2) homogenous *mud*
(3) textured mottled *mud* and *sand*
(4) homogenous *muddy sand*
(5) root-structured *muddy sand*
(6) homogenous *sand*
(7) laminated *sand*
(8) rock *gravel sheets*
(9) *boulder* deposits
(10) interlayed *mud* and *sand*

A summary description of substrate types occurring in each setting is presented in Table 3. The occurrence of these substrate types are noted on most profiles (Figs 5 and 6). These units are also encountered in the stratigraphic profiles.

Stratigraphy

The Quaternary stratigraphy of coastal areas such as Port Darwin is important for several reasons. Firstly, it provides an historical context for the origin and distribution of habitats since the stratigraphy can preserve the short-term to long-term Holocene history of the coast. Consequently it also can provide information on the longevity and maintenance of (mangrove-vegetated) tidal flats and other tidal environments since sedimentary/biotic lithotopes are distinctive stratigraphic units. Finally, the stratigraphy forms the basic framework of both the tidal flat hydrologic system and the tidal flat/hinterland hydrologic exchanges. Since groundwater salinity, recharge and mixing are important elements of mangrove ecosystems, it follows that the stratigraphic array of aquifers and aquatards is an essential part of these systems.

The distinction between Holocene and Pleistocene stratigraphic units was not warranted for purposes of this study. Nevertheless comments as to the age of most of Quaternary sections are presented here: (1) much of the upper parts of the sedimentary accumulations (as illustrated in Fig. 5) are interpreted as Holocene, since the bulk of the deposits appear largely uncemented/unweathered as compared to other Pleistocene tidal flat unts described elsewhere (see Semeniuk 1980); in addition, there is a lack of discrete pedogeneic horizons such as harpans and nodular soils at depth to indicate weathering periods; (2) the profiles of stratigraphy (Fig. 5) illustrate sediment bodies mostly in their correct stratigraphic-topographic positions relative to present sea-level; and (3) many of the stratigraphic units are still depositional at the modern surface. There is a possibility, however, that some of the stratigraphic units at depth (say 4 m below MSL) are of Pleistocene age.

The stratigraphic profile under the sediment-accreted tidal flats has the following components:

(1) *mud wedge;* thick wedge of bioturbated and root-structured mud (some formed under mangrove cover); it is at least 3-4 m thick at its seaward edge and pinches out to landward; this deposit occupies the major portion of an embayment. The wedge interdigitates with gravel/sand deposits developed along the hinterland edge, and with sand deposits of the spits/cheniers.

(2) *mud/sand lens:* hummocky, lensoid shoal deposits (up to 3 m thick) of layered mud and sand formed within channels of tidal creeks.

(3) *muddy sand/gravel sheet:* a sheet (=1 m thick) of muddy sand or gravel sandwiched between the main tidal wedge and the hinterland; this deposit is buried and/or reworked soil/colluvium mixed with tidal mud, and has developed where the tidal flat sediments onlapped the hinterland.

(4) *sand/gravel fan:* a fan-shaped (to deltoid-wedge) deposit of sand, muddy sand or gravel formed where terrestrial drainage has discharged sediment onto the high tidal flats; the alluvial fan interdigitates with the muddy tidal flat wedge.

(5) *sand bar:* a shoe-string or ribbon-shaped sand/shelly sand, up to 500 m wide, 3 000 long and 3-4 m thick, formed as a (mid-) high-tidal to supratidal spit or chenier; it interdigitates with and progrades over mud wedges; these deposits commonly are located at headland entrances to embayments or along wave-exposed portions of islands.

Stratigraphic profiles show that much of the tidal lands are infilled terrestrial lowlands; the stratigraphy records a gradual infilling by one or more of the lithologic/stratigraphic units described above (Fig. 5). On the main tidal flat the sedimentary accumulation has resulted in a wedge of mud, while on sandy coasts the entire stratigraphic interval is composed of sand overlying bedrock. The consistent internal lithology and structure of muddy tidal flat coasts and spit/chenier coasts show that these shore types are long-term stable features which, during the latter Holocene, do not appear to alternate between environmental extremes. For instance, on the spit-lined islands the stratigraphic sections frequently show that a sandy (or muddy sand) spit has interdigitated with tidal flat muds as the shoreline accreted; the wave-exposed parts of islands have consistently acted as loci for spits. On the other hand, some spit/chenier sections indicate a much more recent incursion of a sand bar into the muddy tidal flat environment. Alluvial and colluvial discharge onto tidal zones from fluviatile and hinterland sources continue to accrete sediment and thus maintain the geomorphic units/habitats associated with them.

Groundwater/Soilwater

The salinity of the groundwater and soilwater systems on tidal flats and adjoining hinterland is an important mechanism which regulates mangrove

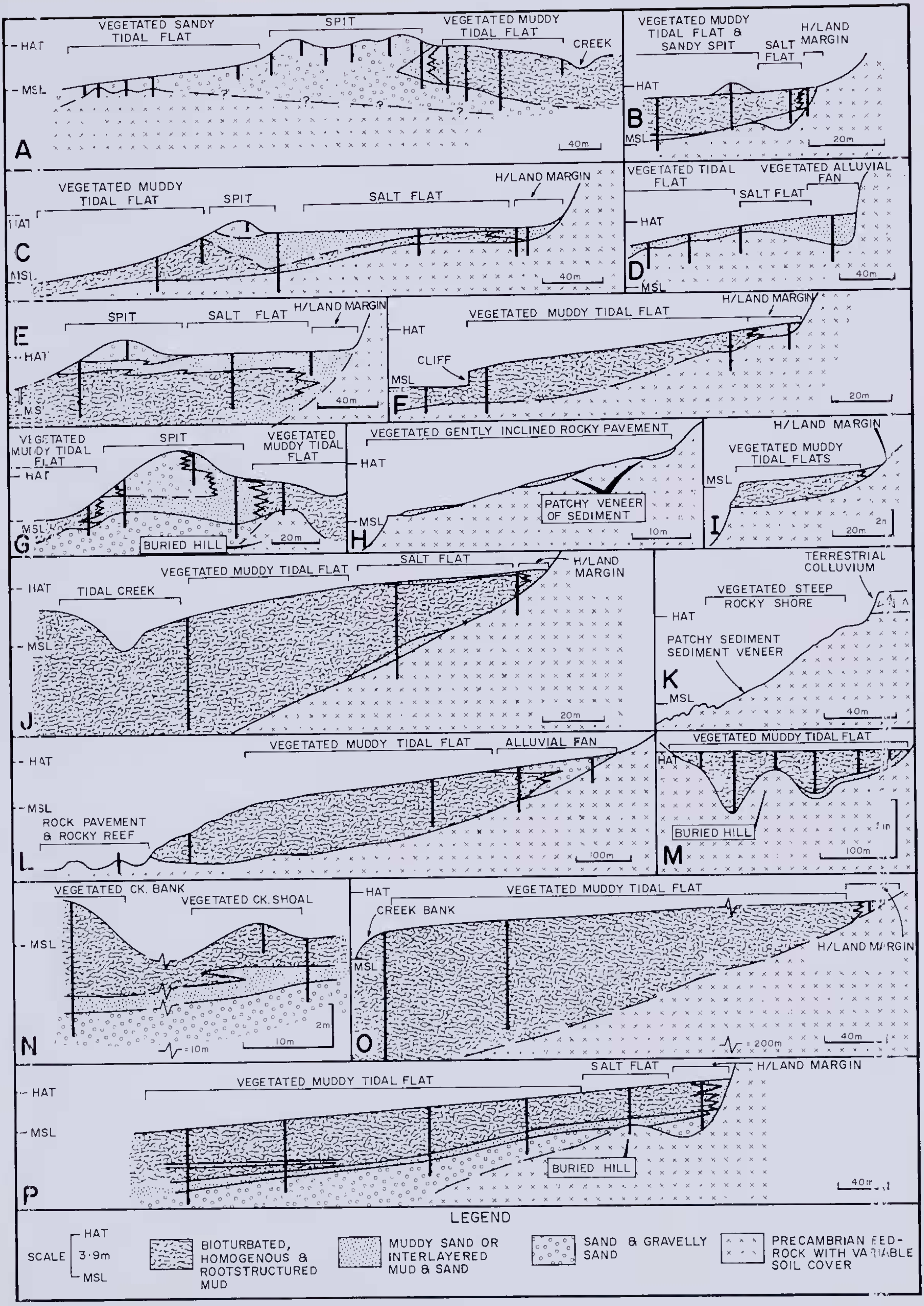

Figure 5.—Stratigraphic profiles across selected tidal areas chosen to illustrate a wide variety of coastal settings. The locations of these profiles are shown on Fig. 1. The profiles illustrate: hinterland bedrock and tidal flat mud relationships (B, C, F, I, J, L); buried hills (A, G, M, P); alluvial fan and hinter land margin relationships with the tidal flat muds (B, C, D, E, F, I, J, L, O); inter relationships between spits and tidal flat muds (A, B, C, E, G); rocky shore stratigraphy (H, K); creek bank and creek shoal relationships (N); island and spit relationships (A); the stratigraphy incised by rivertine processes (I); differentiation of the tidal zone lithofacies into upper-tidal mud, lower tidal/subtidal sand (M, N, P).

Table 4

Main aquifers: properties and groundwater TDS

	GROUNDWATER		
AQUIFER	TYPE OF WATER	SALINITY OF WATER	RECHARGE MECHANISM
Hinterland	fresh water		rainfall
Hinterland/ tidal flat colluvium	contains water developed by mixing of hyper-saline seawater and freshwater seepage from hinterland	up to 130‰ where there is no freshwater seepage; otherwise with freshwater seepage 15-54 ($\bar{x}$31 ± 13)‰	recharged infrequently with seawater by highest tides; recharged perennially or annually by freshwater seepage which precludes any potential extreme hypersalinity
High tidal alluvial fan	contains water developed by mixing of hyper-saline seawater and freshwater seepage from hinterland	1-90‰ dependent on amount of freshwater seepage	recharged infrequently with seawater by highest tides; recharged perennially or annually by freshwater seepage which precludes any potential extreme hyersalinity
Tidal flat mud wedge	contains water approximating to seawater at seaward portion, grades up to very hypersaline at landward portion	gradient: 33-40‰ at MSL,, 41 ± 4‰ mid Rhizophora zone, 89 ± 24‰ at landward edge of mangal grading up to 132‰ across salt flats	recharged daily to fortnightly at levels up to MHWN and MHWS respectively; evapo-trans-piration and evaporation combine to develop a gradient of increasing hypersality
Spits/ cheniers	contains water approximating normal seawater grading up to hypersaline seawater	22-112 ($\bar{x}$ 46 ± 28)‰	depending on tidal level, recharged daily to fortnightly by seawater, and seasonally by meteoric water

populations (MacNae 1968, Chapman 1976, Cintron *et al.* 1978, Semeniuk 1983). Soilwater and groundwater salinity are linked closely to stratigraphy, substrate, recharge mechanisms and evapo-transpiration. There are five main bodies of groundwater (Semeniuk in prep.); there are:

- hinterland groundwater (freshwater)
- hinterland margin groundwater (saline/mixed)
- alluvial fan groundwater (saline/mixed)
- tidal flat groundwater (saline)
- spit/chenier groundwater (saline/mixed)

Each has its own range of salinity as well as its own internal gradients of salinity and chemical composition due to (1) seawater recharge, (2) freshwater recharge, (3) mixing and (4) evaporation. Ultimately there are only two prevailing sources of groundwater: freshwater (discharged from the hinterland), and marine water (recharged daily, fortnighty, varying to half-yearly). The disposition of aquifers and aquatards/aquacludes, and the processes of recharge, groundwater migration, evaporation/transpiration results in a gradient of increasing hypersalinity across tidal flats complicated by a zone of mixing between freshwater (seepage) and tidal flat (hypersaline) groundwater. There is also mixing between seawater (seeping from spits/cheniers) and tidal flat groundwater. The resulting groundwater bodies have various salinities as shown in Table 4 and Figs 6 and 7. Soilwater frequently mirrors the salinity gradients of groundwater because there is mixing vertically due to recharge by tidal waters and to bioturbation by fauna. The essential aspects of soilwater salinity are summarised in Table 3 and Figs 6 and 7).

Hinterland groundwater—The groundwater under the hinterland is freshwater. This seeps to seaward along soil, colluvium and rock interfaces along the hinterland margin and discharges onto the tidal flats in the subsurface. Where it infiltrates the tidal flat it mixes with and dilutes tidal groundwater hypersalinity. The hinterland groundwater is recharged seasonally by meteoric water.

Hinterland margin groundwater/soilwater—This groundwater/soilwater system resides in the muddy colluvial/soil sheet and forms a zone of mixture between tidal flat hypersaline groundwater and freshwater seepage from the hinterland. As a result there is a gradient from brackish water ($15^0/_{00}$ or less) at landward margins to hypersaline ($54^0/_{00}$) where the system adjoins the main tidal flat. Recharge by seawater is infrequent (varying from monthly to twice-yearly); recharge by freshwater runoff and seepage is marked in the wet season and less pronounced, but perennial, in the dry season. The water table is elevated relative to the adjoining high tidal flat system.

Alluvial fan groundwater/soilwater—The water table of the alluvial fans is elevated by freshwater discharge particularly during the wet season where there is combined surface runoff and subsurface seepage. During the dry season there is ongoing subsurface seepage and the water table is still elevated (0.5 m below the ground) relative to the adjoining high tidal flat. The salinity of groundwater and soilwater is freshwater (less than $1^0/_{00}$) at landward parts of the system and grades (via mixing with hypersaline water) up to values of $16\text{-}90^0/_{00}$.

Tidal flat groundwater-soilwater—On the main tidal flat groundwater generally occurs about 10 cm below the surface at seaward mangrove locations during low tide periods. Depending on substrate and tides (neap *vs* spring), it is found progressively deeper until it may be $>$ 1 m deep under salt flats. Groundwater salinity is $38\text{-}40^0/_{00}$ at seaward locations where it is recharged daily, and progressively increases up to highly hypersaline values greater than $100^0/_{00}$ above MHWS where it is recharged fortnightly (Table 4). Groundwater salinity values decrease along the freshwater-influenced hinterland margin and alluvial fans.

Soilwater salinity shows a graded increase in the salinity from $33^0/_{00}$ to $190^0/_{00}$ across the tidal flat, with a decrease in values along the freshwater-influenced hinterland edge and alluvial fans (Table influenced hinterland edge and alluvial fans (Table 3).

Spit/chenier groundwater/soilwater—The spit/chenier groundwater resides within the sand bar stratigraphic unit. The sand is well drained and the water table lies generally more than 0.5 m below the surface. The groundwater salinity where there is daily recharge at seaward parts of the spits/chenier approximates seawater; salinity grades up to values greater than $100^0/_{00}$ at levels of HWS where recharge is fortnightly. On the wider emergent terrestrial spits/cheniers there may be a thin freshwater lens. Soilwater salinity gradients generally follow that of groundwater.

Habitats

The term 'habitat' refers to the area which abiotic factors determine as suitable for colonisation by biota. The important abiotic factors for mangroves include: (1) tidal levels, which determine the frequency of inundation; (2) salinity; (3) substrate types (which are a function of gemorphic setting, tidal exposure and exposure to waves); (4) wave exposure, which determine the amount of reworking of substrates; and (5) terrestrial effects (such as freshwater seepage). These factors are frequently inter-related. For example, salinity gradients in tidal flat soilwater/groundwater are related to frequency of inundation (i.e. tidal levels) and salinity regimes along the hinterland edge are related to terrestrial effects such as freshwater seepage and alluvial input.

Habitat Types

The interplay of tidal level, salinity and substrate type results in a proliferation of tidal zone habitats which, as will be shown later, have distinct biotic assemblages. Habitat types are aggregated for convenience into groups related to geomorphic units and are listed below; the specific habitats which support mangroves are in italics:

- *hinterland fringe;*
- *alluvial fans;*
- *tidal flats* (which may be subdivided on tidal level, substrates and salinity into low tidal flats, *mid to high tidal (mud) flats, mid to high tidal (muddy sand/sand flats)* and salt flats);
- *tidal creeks* (which are comprised of *creek banks, shoal* and *eroded creek mouth* habitats);
- *spits/cheniers* (which may be further subdivided into *mid to high tidal, high tidal* and supratidal/terrestrial parts);
- *rocky shore* (which similarly may be subdivided on tidal levels into subtital, mid to low tidal, *mid to high tidal, high tidal* and supratidal);

All habitat types are widespread but there may be variation in their distribution at the local scale. In addition, there are other tidal zone and subtidal habitats that do not support mangroves but nevertheless comprise part of the Port Darwin tidal-marine system. These include tidal beaches, low tidal sand shoals/sand flats, rocky reefs, rocky pavements and deep water channels. Table 5 summarises data on the essential elements of the main tidal habitats of Port Darwin. Fig. 7 summarises the main salinity and tide-levels gradients that occur within habitats (viz. main tidal flat, hinterland fringe, spit/chenier and alluvial fan).

Mangrove Assemblages According to Habitat

Given that there is a range of habitat types and also a variation of physico-chemical conditions within these habitats, there is therefore a wide range of distinct mangrove assemblages (and zones) that inhabit the coastal environments of Port Darwin. The mangrove assemblages that are recognised are

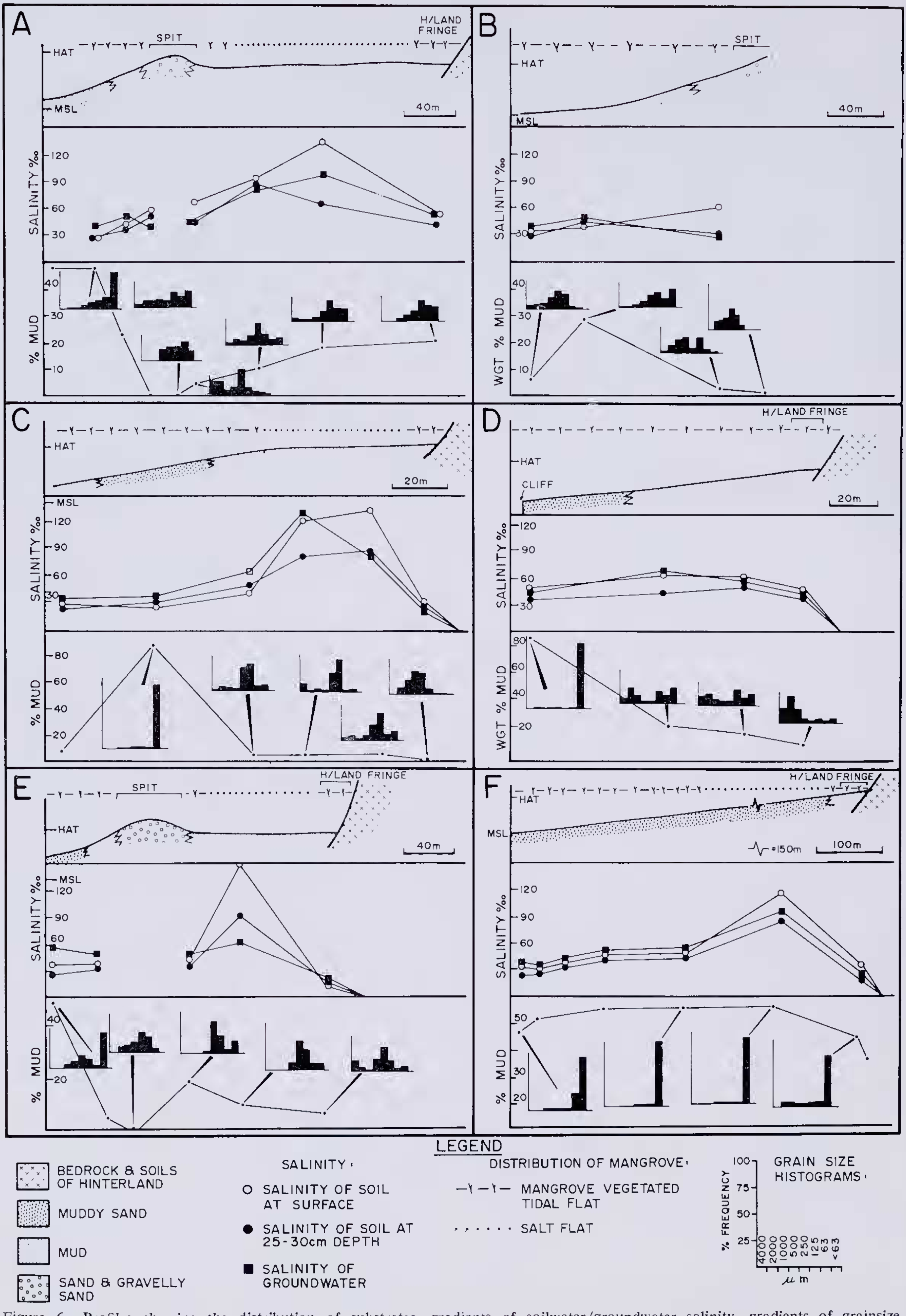

Figure 6.—Profiles showing the distribution of substrates, gradients of soilwater/groundwater salinity, gradients of grainsize and the distribution of mangroves. Profiles across a spit are shown in A, B and E; the tidal flat-hinterland margin relationships are shown in A, C, D, E and F; the gradients across broad tidal flats are shown in C, D and F.

Table 5
Summary of characteristics of the mangrove habitats

HABITAT	DESCRIPTION	MAIN GRADIENTS IMPORTANT FOR MANGROVE ZONATION	COMMENTS ON UNIQUENESS AND THE MAIN FEATURES THAT MAINTAIN HABITATS AND GRADIENTS
Hinterland fringe	moderately steep to gently inclined surface underlain by muddy sand/gravel	salinity; substrate grainsize	habitat is developed and maintained by freshwater seepage and sediment sheet-wash off the hinterland
Alluvial fan	gently inclined surface underlain by muddy sand/gravel sand, and gravel	salinity; substrate grainsize	habitat is developed and maintained by extensive fresh-water seepage, and sediment input along stream/creek channel
Main tidal flat	gently inclined surface between MSL and HAT, underlain mainly by mud but depending on relationship to spit, may be underlain by sand	frequency of inundation; salinity	habitat surface is maintained by sedimentation/erosion; salinity regimes are maintained by marine water recharge, evaporation and seasonal meteoric water recharge
Creek bank	steep to moderately inclined muddy surface between MSL and HWN	frequency of inundation; salinity; drainage	habitat surface is maintained by erosion; steep banks and bioexcavation/burrows ensure rapid drainage
Creek shoal and eroded creek mouth	hummocky muddy surface MSL	distinct gradients not evident	habitat surface is maintained by sedimentation alternating with erosion
Spit/ chenier	steep to moderately inclined surface underlain by sand, gravelly sand and muddy sand	frequency of inundation; salinity; substrate grainsize; drainage	habitat surface is maintained by sedimentation/erosion; salinity regimes maintained by marine water recharge, evaporation and periodic freshwater seepage
Rocky shore	steep to moderately inclined surface underlain by bedrock or boulder/pebble sheet	frequency of inundation; salinity	habitat surface is maintained by erosion/sedimentation; very shallow soil or no soil; marked surface water runoff, salinity regimes maintained by marine water recharge

restricted to the medium-scale habitat type so that maps of habitat distribution virtually represent areas of these assemblages (Figs 3 and 4). These assemblages are termed as follows:

(1) "hinterland fringe" assemblage
(2) "alluvial fan" assemblage
(3) "main tidal flat" assemblage
(4) "creek bank" assemblage
(5) "creek shoal" assemblage
(6) "creek mouth" assemblage
(7) "spit/chenier fringe" assemblage
(8) "rocky shore" assemblage.

The occurrence of these assemblages according to habitat, and the components of these assemblages are summariesd in Table 6. The detailed description of the zones within the assemblage forms the subject of another paper in preparation.

Synthesis

There are a number of aspects of the Port Darwin environment that are useful to understanding mangrove distribution, mangrove assemblage variation and population maintenance. Firstly, at the large scale, there are a wide range of mangrove settings developed as a result of geomorphic history. Thus riverine, narrow-embayment, broad-embayment, spit/chenier lined-embayment and island environments are developed in response to variable interaction of (1) oceanic processes, (of sedimentation, erosion, wave action), and (2) riverine processes (of sedimentation, erosion), and (3) terrestrial processes (of weathering, erosion, transport).

Secondly, within a given (large-scale) setting there is a variable but recurring array of geomorphic units and habitats which determine the distribution of broad mangrove assemblages; these units reflect (medium-scale) geomorphology and its history. The resulting units are a product of marine (tidal-flat) sedimentation; tidal erosion, wave action, terrestrial transport/sedimentation and freshwater/marine interactions.

Finally, there is variation within habitats since there are a range of small-scale physico-chemical gradients within geomorphic/habitat units; these gradients

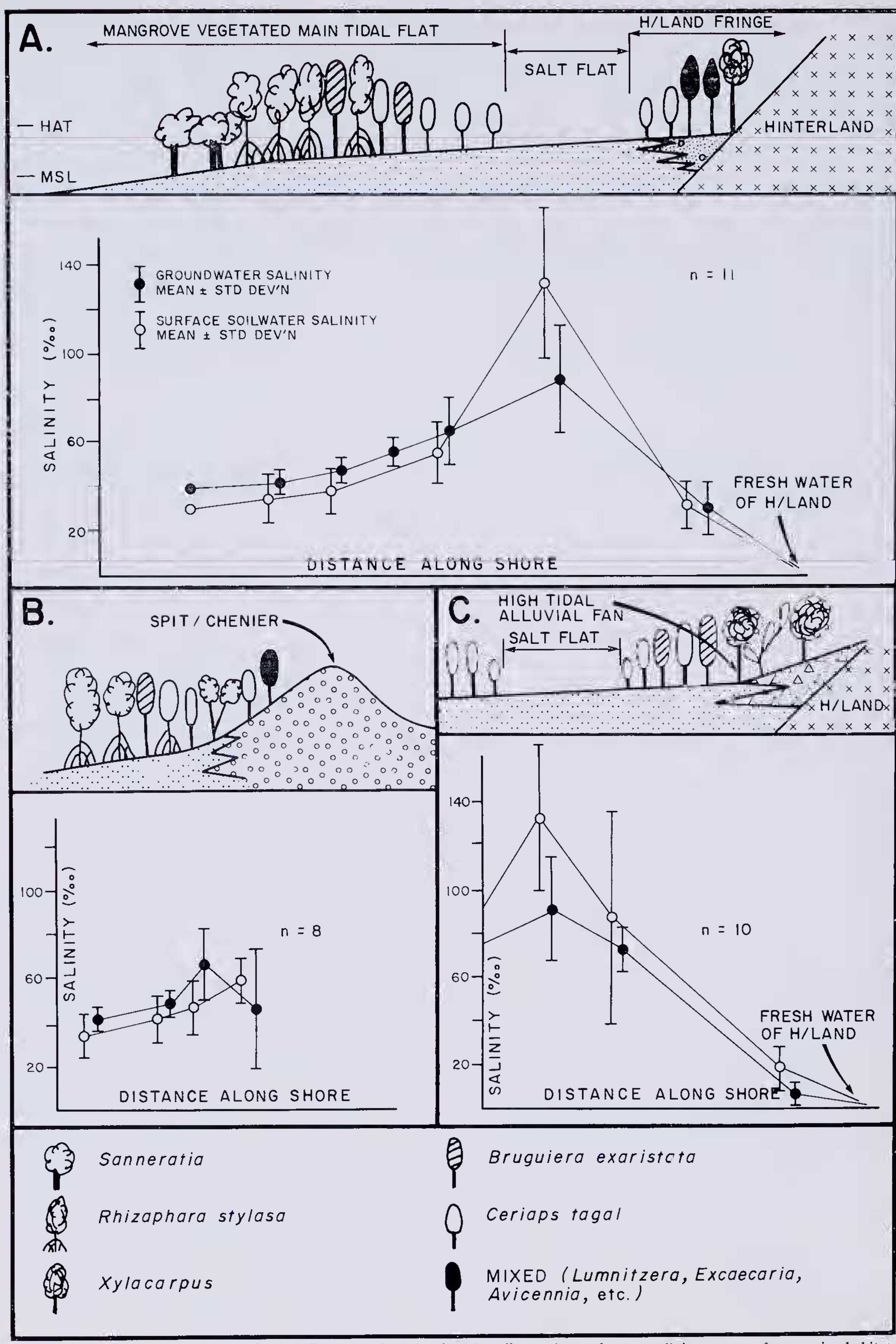

Figure 7.—Summary diagram showing gradients in tidal level and soilwater/groundwater salinity across four main habitats (*viz* main tidal flat, hinterland margin, alluvial fan and spit/chenier). The number 'n' refers to the number of transects used to compile this summary information and to derive the mean ± SD value for the salinity.

Table 6

Main components of the biotic assemblages and their occurrence according to habitat

HABITAT		ASSEMBLAGE	MAIN COMPONENTS
HINTERLAND/ TIDAL FLAT MARGIN		"Hinterland fringe"	Lumnitzera racemosa, Ceriops tagal, Excoecaria agallocha, Xylocarpus sp., Avicennia marina
HIGH TIDAL ALLUVIAL FAN		"Alluvial fan" mangal	Ceriops tagal, Bruguiera exaristata, Lumnizera racemosa, Excoecaria agallocha, Xylocarpus sp., Scyphiphora hydrophylacea, Diospyros ferrea and Rhizophora stylosa
MAIN TIDAL FLAT		"Main tidal flat mangal"	seaward Sonneratia zone with Aegiceras and Avicennia, followed by Rhizophora zone, followed by a zone of mixed Rhizophora, Bruguiera, Ceriops, Avicennia and Aegialitis, followed by Ceriops zone
TIDAL CREEKS	banks	"Creek bank"	Rhizophora stylosa, Camptostemon schultzii, Bruguiera parviflora Ceriops decandra, Ceriops tagal, Aegiceras corniculatum, Avicennia marina
	shoals	"Creek shoal"	Aegiceras corniculatum, Aegialitis annulata
	mouths	"Creek mouth"	Sonneratia alba, Aegiceras corniculatum, Aegialitis annulata
SPITS/ CHENIERS		"Spit/ chenier fringe"	below HWS: Ceriops tagal, Bruguiera exaristata, Rhizophora stylosa, Xylocarpus sp., Osbornia octodonta, Avicennia marina followed by Hibiscus tilliaceus, Lumnitzera racemosa, Excoecaria agallocha, Pemphis acidula above HWS
ROCKY HEADLANDS		"Rocky shore"	Sonneratia followed by mixed zone Rhizophora, Camptostemon, Aegiceras, Avicennia, followed by mixed zone of Ceriops, Osbornia, Excoecaria, Xylocarpus, Hibiscus, Pemphis.

(grain size, variability of soils, inundation frequency and salinity) are responsible for a profusion of internal zonation in mangrove assemblages. The key factors for developing gradients therefore are: (1) tidal level (hence inundation frequency), (2) the interplay between marine water recharge, freshwater recharge, and evaporation, which result in salinity regimes and salinity gradients, and (3) the interplay between tidal level and wave action which result in substrate variability. The key geomorphic and physico-chemical processes that maintain the various mangrove habitats are presented in Table 5.

In summary, in Port Darwin the interplay of various physico-chemical processes at various scales has resulted in a range of mangrove settings, mangrove habitats and various types of gradients within habitats. The resultant mosaic of mangrove assemblages and zones essentially reflect the variation in these physico-chemical processes and products.

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